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Nitrogen and Phosphorus Enrichment Effects on Nutrient Supply in Reservoirs: a Small-Scale Approach

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I. Summary

Eutrophication is a problem in many lakes, but the reduction of nutrient inputs such as nitrogen (N) and phosphorus (P) to combat eutrophication can lead to an oligotrophic state, which may be unable to support healthy aquatic ecosystems. This study examined how different rates of chemical fertilization with N and P during times of nutrient limitation (mid-summer) could affect particulate N and C concentrations in four lakes in northwest Arkansas. Fertilization experiments were conducted in microcosms during the month of July 2014. Water samples from each lake were collected and divided into six treatments: control, P-only, N:P 10, 20, 40, and 80. Concentrations of particulate N and C were quantified using elemental analysis. For each lake, particulate N and C generally increased as N:P supply increased. The lack of a significant difference between higher level N:P treatments (N:P 20 and 40 versus N:P 80) suggests on a whole-lake scale, a lower rate of fertilizer addition can be used and still achieve the same effects seen with greater N:P treatments.

II. Introduction

Worldwide, there are very few water bodies left unaffected by anthropogenic activities (Smith et al 2006, Thompson 2013). One of the most common problems facing water bodies today is eutrophication, the enhanced concentration of nutrients (Smith et al 1999, Anders and Ashley 2007, Smith and Schindler 2009). There are many detrimental effects of eutrophication to water bodies including increased occurrence of harmful algal blooms (HABs), reduction in species diversity, oxygen depletion, and decreased aesthetic qualities, to name a few (Smith and Schindler 2009). Eutrophication is a natural process in some ecosystems; however, anthropogenic effects on the nitrogen (N) and phosphorus (P) cycle have been implicated worldwide in dramatic changes to aquatic ecosystems (Smith et al 1999, Elser et al 2007). Though naturally N and P are limiting nutrients for primary production, amplification by human activities of the global N and P cycles of 100% and 400%, respectively, has fueled excessive production in many ecosystems in the process referred to as cultural eutrophication. (Elser et al 2007, Smith and Schindler 2009).

While N and P are often gain attention for their detrimental effects on aquatic ecosystems, both of these nutrients are essential in some amount to support healthy and diverse aquatic food webs. (Elser et al 2007). In addition to other functions, N is necessary for protein synthesis, while both N and P are essential components of DNA (Conley et al 2009). Nitrogen and P are critical for phytoplankton growth, which are the base of most aquatic food webs. Nitrogen and P are the principal nutrients regulating primary productivity and thus higher trophic level biomass in aquatic ecosystems (Smith 1982). Phosphorus has previously been identified as the main nutrient limiting primary production in lakes (Schindler 1977), as fish biomass is positively correlated with P level in lakes (Ney et al 1990). However, recent studies have shown that N can be equally or even more limiting (Elser et al 2007). If N and Pare not present in sufficient amounts to support healthy phytoplankton growth, then higher level food webs cannot be supported (Lindeman 1942, Ney 1996).

In conjunction with the passing of the Clean Water Act forty-two years ago (Clean Water Act 1972), water quality management largely shifted to a reduction of these naturally occurring nutrients, a process referred to as cultural oligotrophication (Anders and Ashley 2007). With this trend, the beneficial effects of N and P on aquatic ecosystems are largely ignored in favor of limiting nutrient inputs in order to have clear water that is aesthetically pleasing (Anders and Ashley 2007). The passing of the Clean Water Act required states to designate uses for their lakes and streams and then design and implement standards to support those uses (Clean Water Act 1972). If a lake is designated for primary contact recreation or for drinking water, then working to reduce the external nutrient load to that lake will help achieve that goal. In this case, a clean appearance may be much more important than a healthy, productive ecosystem. However, many water bodies designated for primary contact recreation or for drinking water are also used for recreational fishing, a sport that contributes billions of dollars annually to the United States economy (American Sportfishing Association 2012). Low nutrient concentrations are undesirable if those lakes are also designated to support aquatic life (Boyd and Sowles 1978). In instances where these uses collide, stewards of water bodies encounter the Clear Water Paradox: Users of these water bodies want the benefits of ecosystem services such as healthy fish populations, but also want to see clear, aesthetically pleasing waters. These benefits are often limited by water quality standards that limit biological productivity (Anders and Ashley 2007). In such lakes with multiple uses, a balance must be struck between extreme algal growth as a result of excessive primary production and nutrient-poor waters unsustainable for healthy, robust fish populations (Ney 1996). In these cases, it is necessary to manage water quality for conditions supporting all of the uses for which the water body is designated.

The trophic state is the level of biological productivity of both plants and animals in an ecosystem (Carlson 1977). The continuum of trophic states is divided between oligotrophic, mesotrophic, and eutrophic (Carlson 1977). Criteria have been developed for classification of water bodies into trophic states based on relationships between Secchi depth, chlorophyll-a (chl-a) concentration, and total phosphorus (TP) concentration (Carlson 1977, Smith et al 1999) (Table 1). Oligotrophic lakes are characterized by low annual water temperature; short, unproductive growing seasons; underlying granite bedrock; and relatively nutrient-poor watersheds, leading to extremely clear, nutrient poor water (Anders and Ashley 2007). Eutrophic lakes are characterized by elevated nutrient loads from the surrounding watershed; long, highly productive growing seasons that encourage the growth of nuisance aquatic plants and algae; and greenish-brown water that may look, taste, and smell bad (Anders and Ashley 2007). The middle ground is mesotrophic: lakes that exhibit characteristics of both oligotrophic and eutrophic lakes, and thus can support a variety of designated uses. Therefore, today many fisheries managers manage nutrient levels to achieve mesotrophic conditions in lakes with multiple designated uses. (Stockner et al 2000, Thompson 2013).

Mesotrophic lakes usually support adequate primary production and thus can support higher-level food webs without fueling excessive growth (Stockner et al 2000). However, the implementation of a lake fertilization plan not only requires solid understanding of the effects of nutrient additions will affect lake conditions, but also represents a significant economic cost. Thus, before adding nutrients on a whole-lake scale, it is necessary to have some prior knowledge and understanding of the extent of the lake response to fertilization treatments at varying rates in order to avoid over-fertilization and wasted resources. Numerous small-sale laboratory fertilization experiments have been conducted to examine nutrient limitation (McDiffett 1980, Elser et al 2007). Though there has been some consensus that the results of such small-scale laboratory experiments do not take into account long-term effects on the lake ecosystem (Schindler et al 2008), employing small scale studies before applying nutrients on a whole-lake scale can be valuable in informing water quality and fisheries managers on possible whole-lake response to nutrient additions (Schindler 2012). By conducting small-scale experiments before fertilization, not only can unforeseen environmental consequences of fertilization be limited, but excessive economic costs can be avoided.

III. Objectives & Research Hypotheses

The objective of this study was to explore the effects of varying rates of N and P fertilizer additions on primary production using microcosm experiments with water from four nutrient-managed lakes. The specific goals of the study were to 1) assess the potential effects of chemical fertilizer additions on particulate N and C in four lakes and 2) determine an optimal rate of fertilization in each lake. The data collected to achieve these goals came from microcosm biomass data. The main hypothesis for the study was because of mid-summer nutrient limitation, increase in the rate of N:P chemical fertilization will cause increase in particulate N and C. A secondary hypothesis based on the findings of Elser et al 2007 was simultaneous inputs of N and P will result in a greater response in particulate N and C concentrations than P additions alone.

IV. Materials & Methods

Study Sites

The study was conducted in four recreational sport fishing reservoirs in the Little Sugar Creek watershed of Northwest Arkansas (Figure 1). Lake Ann (36°28'23.98"N, 94°13'30.07"W), Lake Avalon (36°28'20.39"N, 94°16'20.46"W), Lake Lomond (36°28'3.80"N, 94°19'37.07"W), and Lake Windsor (36°27'21.09"N, 94°15'48.20"W) (Figure 2) are owned and managed by the Bella Vista Property Owners Association (BVPOA) to support multiple recreational use and meet state water quality standards for primary contact recreation as stated by the Arkansas Pollution Control and Ecology Commission Regulation 2 (Nutrient Management Plan for Bella Vista Lakes 2010). While the Bella Vista lakes are technically man-made reservoirs, they are subject to the same biological, chemical, and physical characteristics of natural lakes (Rast and

Straškraba 2000) and water quality is measured using the same parameters as in natural lakes. They have the characteristic dendritic shape of reservoirs and represent an intermediate aquatic system between a flowing water body and a lake, with more riverine characteristics towards the upstream end of the reservoir and more lacustrine characteristics downstream towards the dammed end (Rast and Straškraba 2000). Water sampling for this study took place in the lacustrine zone near the dammed end of these reservoirs. For names sake, the reservoirs in Bella Vista include in this study are henceforth referred to as lakes. The lakes vary greatly in their size and watershed area and characteristics (Table 2). In the 1990s, the BVPOA began managing the lakes with chemical fertilizers to increase biological productivity, but fertilization ceased in 2002 because of over-fertilization leading to poor water quality and complaints from property owners. After 2002, data showed that biological productivity and fisheries in the Bella Vista lakes had decreased as a result of the reduced nutrient inputs. Past data has indicated that these reservoirs become limited in nitrate (NO_3) during the summer months, prompting the need for chemical fertilization (Figure 3, 4) and indicating the need for a nutrient management plan that supports healthy fisheries while balancing other uses such as swimming, boating, and aesthetics. The current nutrient management plan was implemented in 2010 and includes consistent water quality sampling and nutrient management based on monitoring data (Nutrient Management Plan for Bella Vista Lakes 2010).

Experimental Design – Microcosm Fertilization Experiments

Microcosm experiments were conducted in July of 2014 to observe the effects of fertilization on biological productivity during the growing season. Temperatures in July 2014 were about 3ºC cooler than the 30 year climatology and precipitation was about 5 cm less than average (U.S. Climate Data 2016, Weather Spark 2016) (Table 5, Figure 5). During routine water quality sampling as part of the BVPOA Nutrient Management Plan, vertically-integrated water samples from the photic zone of each lake were collected using a 4-L Van Dorn horizontal sampler (Alpha water sampler, Wildco, Yulee, FL) to create a composite sample. The composite sample from each lake was divided into 18 1-L cubitainers with triplicates of each fertilizer treatment: control, P-only, and N:P 10, 20, 40, and 80. Nitrogen and P were added from stock solution based on each lake's initial Secchi depth and total N (TN) and total P (TP) and target N:P (Table 6, 7). The volume of P added was kept constant and volume of N added was changed depending on the N:P treatment. The microcosms were then randomly assorted and placed in a water bath with overhead UV lighting to stimulate phytoplankton growth. The Secchi depth at the time of water collection was used to calculate the initial TP concentration and initial chlorophyll-a concentration based on the Carlson Trophic State Index (Carlson 1977) and initial concentrations of particulate N and C were found using elemental analysis (NC Soil Analyzer, Flash 2000 Organic Elemental Analyzer, Thermo Scientific, Lakewood, NJ) (APHA 2005) (Table 8).

The cubitainers were incubated in the water bath for six days with in-vivo fluorescence samples from each cubitainer measured on the date of the initial experimental setup and every 1 to 2 days during experiments. When in-vivo fluorescence measurements began to indicate a decline in phytoplankton biomass, the microcosm experiments were concluded (Figure 6). Fifty to two hundred mL of water from each cubitainer was mixed and filtered for analysis of particulate C and N content using elemental analysis. The effect of fertilization rate was tested using a one-way ANOVA using SAS 9.3 (SAS Institute Inc. Cary, N.C.) with a threshold p-value of 0.05..

V. Results

In the Lake Ann microcosms, particulate N concentrations generally increased with increased N:P supply. Significant increases in particulate N occurred between the control and P-only treatments, the N:P 10 treatment, and the N:P 20, 40, and 80 treatments (Figure 7, p-value = 0.0003). The N:P 10 treatment did not differ from the control and P-only treatments or the N:P 20, 40, and 80 treatments. Particulate C in the Lake Ann microcosms also increased with increased N:P supply. There was no increase in particulate C between the control and P-only treatments or the P-only and N:P 10 treatments, but the N:P 20, 40, and 80 treatments increased from the control, P-only, and N:P 10 treatments (Figure 7, p-value = <0.0001) . There was no pattern between treatments regarding the C:N ratio from the microcosm samples, and there was no difference between the C:N of any of the groups (Figure 7, p-value = 0.4617).

The microcosms from Lake Avalon showed a similar pattern to that of the Lake Ann microcosms. There was no increase in particulate N between the control, P-only, N:P 10, 20, and 40 treatments. The N:P 80 treatment increased over the control and P-only treatments, but not from the N:P 10, 20 and 40 treatments. (Figure 8, p-value = 0.0146). Increases in particulate C were measured between the control and P-only treatments and the N:P 40 and 80 treatments, with no difference in the N:P 10 and 20 groups from either the control and P-only treatments or the N:P 40 and 80 treatments (Figure 8, , p-value = 0.0031). Again, there was no obvious pattern between treatments for the C:N ratio and all treatments were similar (Figure 8, ,p-value = 0.1630).

In Lake Lomond microcosms, there was not as strong of an increasing pattern between treatments and there was no increase in particulate N between the control, P-only, N:P 10, 20, and 40 treatments. The N:P 40 and 80 treatments were the same, but the N:P 80 was the only treatment that had any increase from the control treatment (Figure 9, , p-value = 0.0044). Particulate C in the Lake Lomond microcosms increased with increasing N:P supply. The control and P-only treatments and the P-only, N:P 10, 20, and 40 and N:P treatments were not different However, the particulate C in the N:P 80 treatment was greater than all other treatments (Figure 9, p-value = <0.0001). Carbon:N again showed no difference between treatments (Figure 9, p-value = 0.1584).

In the Lake Windsor microcosms, there was no difference in particulate N between the control, P-only, and N:P 10 treatments and no difference between the N:P 10, 20, and 40 treatments. Particulate N in the N:P 20, 40, and 80 treatments was also similar, but particulate N in the N:P 80 was greater than the control, P-only, and N:P 10 treatments (Figure 10, , p-value = 0.0003) . There was not a strong increasing trend in particulate C with increasing N:P. The P-only treatment was lower than the N:P 80 treatment were different from each other; otherwise the treatments were all similar (Figure10 , p-value = 0.0492). Only the microcosms from Lake Windsor showed a significant difference in C:N. Phosphorus-only, N:P 10, and N:P 20 were all than the control (Figure 10, p-value = 0.0144).

VI. Discussion

. Results showed that additions of both N and P chemical fertilizers in the microcosms increased both particulate N and C in these reservoirs during the month of July, when nutrient concentrations are especially limited. In general, as the added N:P supply in each microcosm increased, the particulate N and C increased as well, showing that in general, on a whole-lake scale, these reservoirs would most likely show a nutrient level response proportionate with fertilization rate.

Among the moderate (N:P 20 and 40) and high(N:P 80) treatments, there frequently was no difference between different rates of fertilization on particulate N and C. For example, in the Lake Ann microcosms, there was no increase in particulate N between the N:P 10, 20, 40, and 80 treatments, and with particulate C there was no increase between the N:P 20, 40, and 80 treatments. A similar pattern was seen in the Lake Avalon microcosms where there was no increase in particulate N between the N:P 10, 20, 40, and 80 treatments, and no significant difference in particulate C between the N:P 10, 20, 40, and 80 treatments . Lake Lomond microcosms showed an increase in particulate N from the control at the N:P 40 and 80 treatments and an increase in particulate C at the N:P 80 treatment. The Lake Windsor microcosms also followed a similar pattern in which there was no increase in particulate N between the N:P 20, 40, and 80 treatments and no difference in particulate C between the N:P 10, 20, 40, and 80 treatments.

From this pattern, it may be possible that a moderate fertilization rate such as N:P 20 or 40 has the potential to achieve the same effects on nutrient supply as a higher fertilization rate such as N:P 80 in these lakes. By fertilizing at the lowest rate needed to produce a positive response, the risk of over-fertilization can be avoided, thus avoiding the possibility of over-production leading to eutrophic conditions and the negative consequences accompanying it. Besides environmental problems and avoiding complaints from property owners regarding HABs and unpleasant look and smell, using the lowest rate of fertilization needed to produce a positive response can also greatly reduce economic costs. At the time of this study, the BVPOA was using a combination of Dunn's 'Trophy Grower' liquid pond fertilizer (10-34-0) with a recommended application rate of 1-2 gallons per surface acre and a cost of $12.95 per gallon (Dunn's Fish Farm 2016), as well as a dozen to hundreds of bags of urea fertilizer (46-0-0), of which the commodity price of a 50-lb bag in July 2014 was about $8 (IndexMundi 2016). Added together, the cost of fertilization in these reservoirs during the summer months could be anywhere between about $2,500 at the lowest fertilization rate of N:P 10 in Lake Avalon to over $100,000 at the highest fertilization rate of N:P 80 in Lake Lomond (Table 9). Thus, there is a definite economic benefit to gathering information on a smaller, less-expensive scale regarding how these reservoirs may respond to chemical fertilization and the minimum amount of fertilizer needed to achieve the desired response in. Previous experiments in Bella Vista (Thompson 2013) have indicated that on a whole-ecosystem scale, these reservoirs are likely to respond as predicted based on microcosm results.

VII. Conclusion

In conclusion, additions of chemical N and P fertilizers can stimulate primary production and phytoplankton growth and increase nutrient concentrations. During times of nutrient limitation such as mid-summer, chemical fertilization with N and P fertilizers can be used to stimulate primary productivity in multi-use water bodies in order to achieve mesotrophic conditions supporting multiple uses. Using a moderate rate of fertilization may achieve the same effects as higher fertilization rates, reducing costs and decreasing the possibility of bringing about undesirable environmental conditions. Small-scale fertilization experiments can be used to inform on possible whole-lake ecosystem response before beginning a large-scale fertilization program.

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Tables and Figures

Table 1. Average total nitrogen (TN), total phosphorus (TP), chlorophyll-a (chl-a), and Secchi depth of each trophic state (Smith et al 1999).

Trophic state	TN (mg/m^3)	TP (mg/m^3)	chl-a (mg/m^3)	Secchi depth (m)
Oligotrophic	<350	<10	<3.5	>4
Mesotrophic	350-650	10-30	3.5-9	2-4
Eutrophic	650-1200	30-100	9-25	1-2

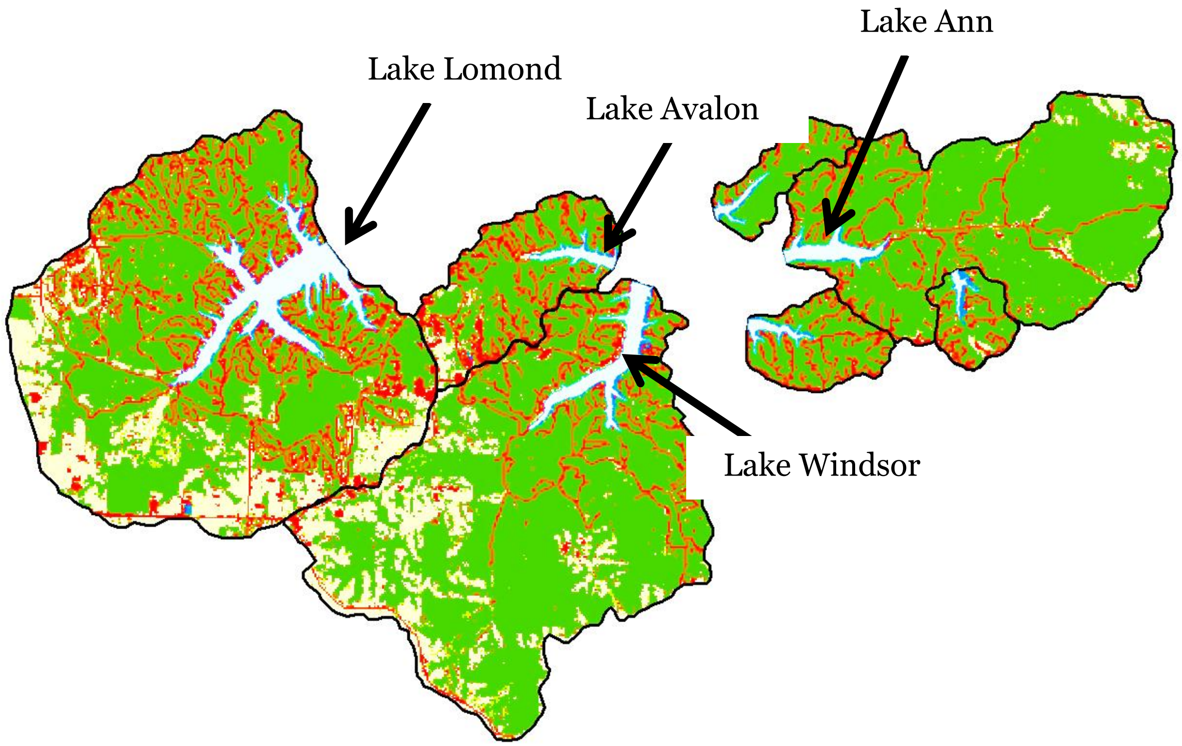

Figure 1. Map of four lakes and their respective watersheds in Bella Vista, Arkansas generated from GIS (Global Information System) satellite data. Maps also show land use. Green areas are forest; yellow areas are pasture; red areas are urban (Nutrient Management Plan for Bella Vista Lakes 2010).

Figure 2. Google Earth satellite image of Lakes Ann, Avalon, Lomond, and Windsor in Bella Vista, Arkansas.

Table 2. Watershed and lake size conversions of the four lakes included in the study (Nutrient Management Plan for Bella Vista Lakes 2010).

Lake	Watershed Area (km^2)	Lake Surface Area (km^2)	Watershed Area (acres)	Lake Surface Area (acres)	Maximum Depth (m_
Ann	19.5	0.420	4,820	104	16.2
Avalon	6.00	0.240	1,480	59.7	15.2
Lomond	34.0	2.25	8,410	557	24.4
Windsor	29.8	0.910	7,360	226	24.1

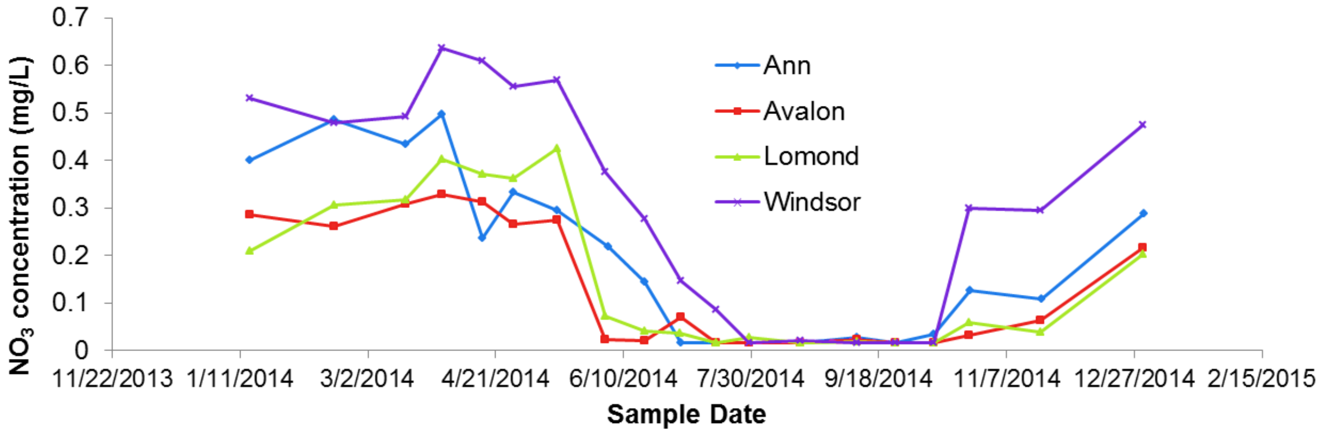

Figure 3. NO_3 concentration in Lakes Avalon, Ann, Lomond, and Windsor from January to December 2014.

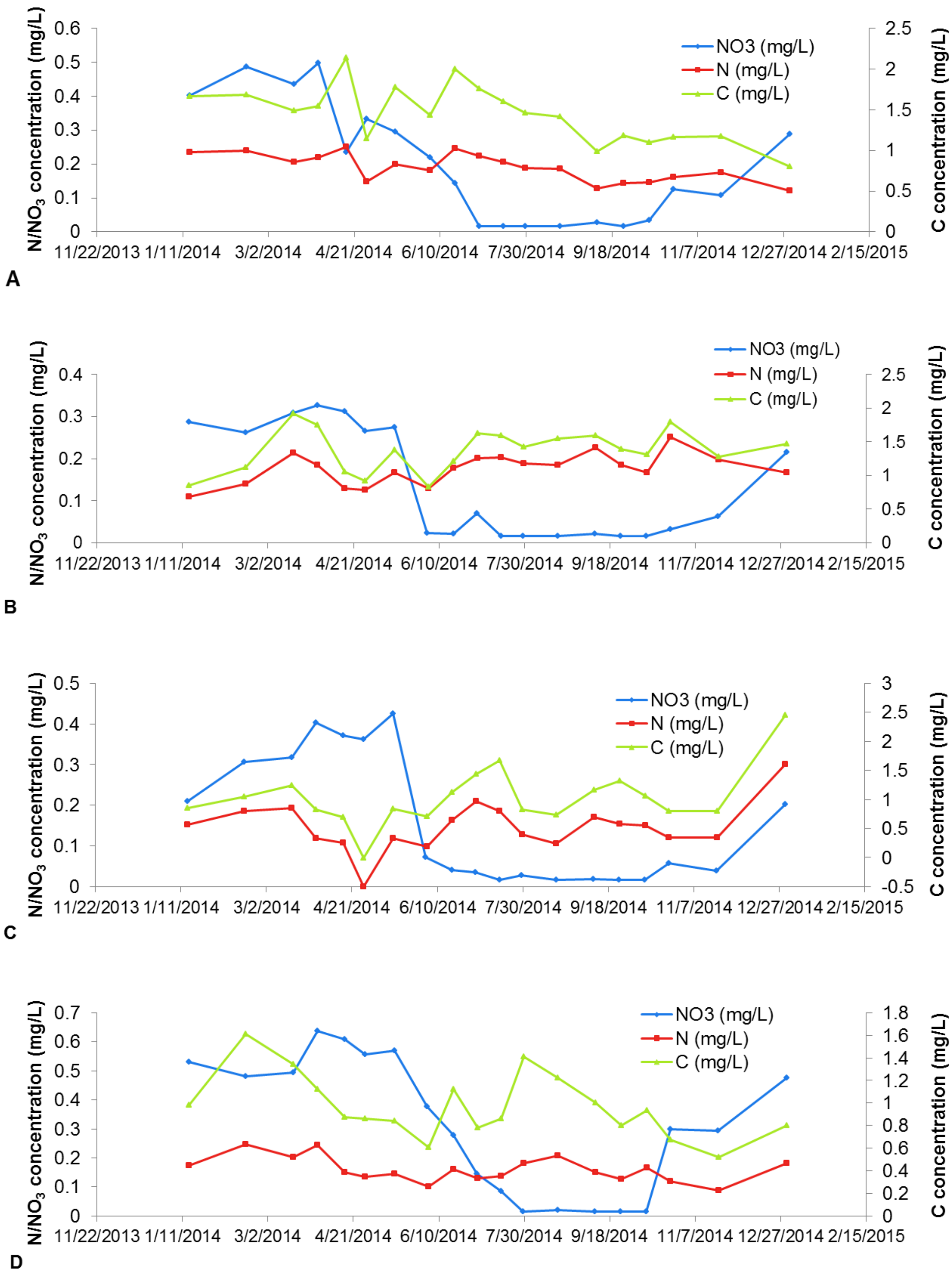

Figure 4. NO_3, particulate N, and particulate C concentration in (A) Lake Ann, (B) Lake Avalon, (C) Lake Lomond, and (D) Lake Windsor from January to December 2014.

Table 5. Average weather and 30-year climatology data for the Northwest Arkansas region from January 2014 to July 2014 (U.S. Climate Data 2016).

Month	Average Monthly High (ºC)	30 Year Average Monthly High (ºC)	Average Monthly Low (ºC)	30 Year Average Monthly Low (ºC)	Average Monthly Precipitation (cm)	30 Year Average Monthly Precipitation (cm)
January	-5.2	7.8	-12	-3.3	0.71	6.5
February	-6.7	11	-12	4.4	0.25	6.1
March	12	15	-1.2	3.3	9.7	10.2
April	20	21	7.1	8.3	8.7	11
May	24	24	14	13	14	13
June	28	29	19	18	11	12
July	29	32	18	21	3.5	8.2

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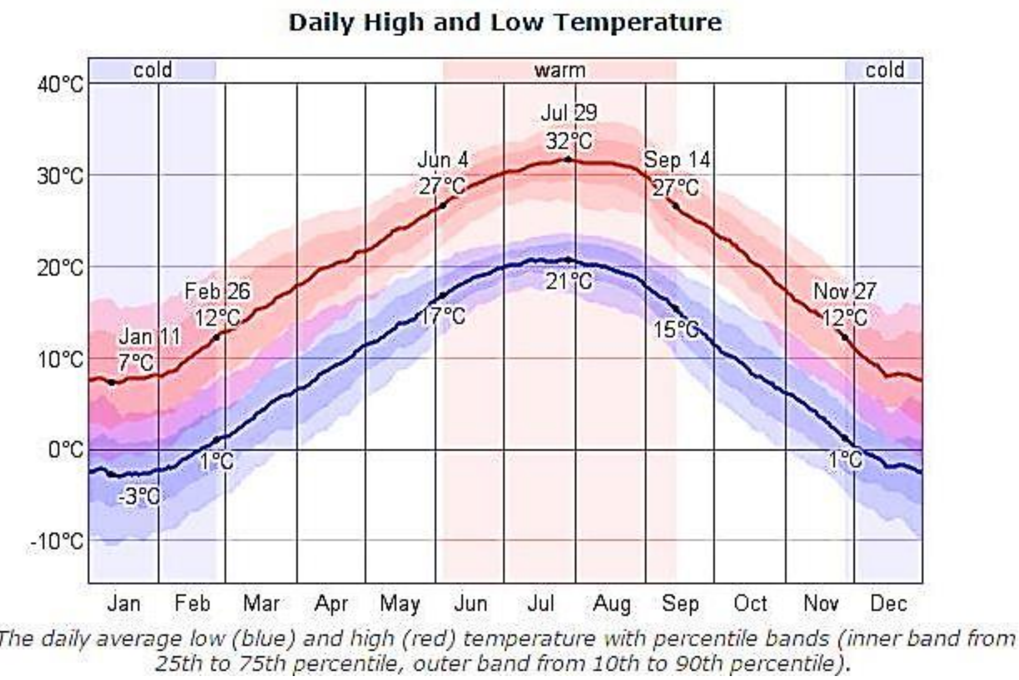

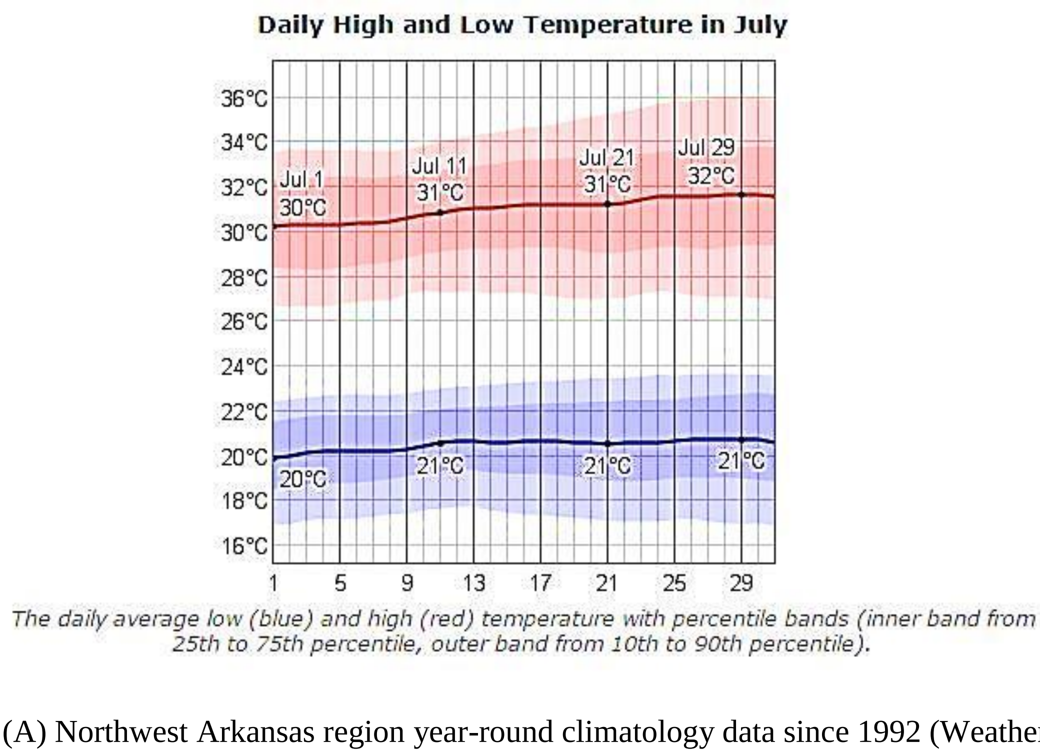

Figure 5 (A) Northwest Arkansas region year-round climatology data since 1992 (WeatherSpark 2016). (B) Average July temperatures based in Northwest Arkansas based on climatology data since 1992 (WeatherSpark 2016).

Table 6. Example microcosm fertilizer rate calculator (Lake Ann). The Secchi depth at the time of water collection was used to calculate the initial total phosphorus (TP) and the TP and total nitrogen (TN) needed to achieve a desired Secchi depth and chlorophyll-a (chl-a) concentration.

Microcosm Fertilizer Calculator			
2.80	Current Secchi Depth		
4.40	Current Chlorophyll-a		
18.3	Current TP (µg/L)		
1.50	Target Secchi Depth (m)		
11.1	Target Chl-a (µg/L)		
2.50	Target Response Ratio		
34.5	Target TP (µg/L)		
16.3	TP Needed (ug/L)		
73.5	TN Needed (µg/L)	10	N:P Supply (molar)
147		20	
294		40	
588		80	

Table 7. Microcosm nutrient addition calculator. The volume of stock N and P solution that needed to be added was calculated based on TP and TN required from Table 3.

Microcosm Nutrient Addition Calculator				
Cubitainer Volume (L):		0.9		
Stock Solution Conc. (mg/L)		Volume Needed (mL)		N:P Supply (molar)
P	N	P	N	
10	100	1.46	0.66	10
			1.32	20
			2.65	40
			5.29	80

Table 8. Initial Secchi depth, total phosphorus (TP), chlorophyll-a (chl-a), particulate nitrogen (N), particulate carbon (C), and trophic state of Lakes Ann, Avalon, Lomond, and Windsor at time of water collection for microcosm experiments.

Lake	Secchi Depth (m)	TP (mg/L)	Chl-a (µg/L)	Particulate N (mg/L)	Particulate C (mg/L)	Trophic State
Ann	2.8	0.018	4.4	0.19	1.1	Mesotrophic
Avalon	2.3	0.023	5.9	0.24	1.4	Mesotrophic
Lomond	4.0	0.013	2.6	0.20	1.3	Meso-Oligotrophic
Windsor	3.7	0.014	2.9	0.18	1.0	Meso-Oligotrophic

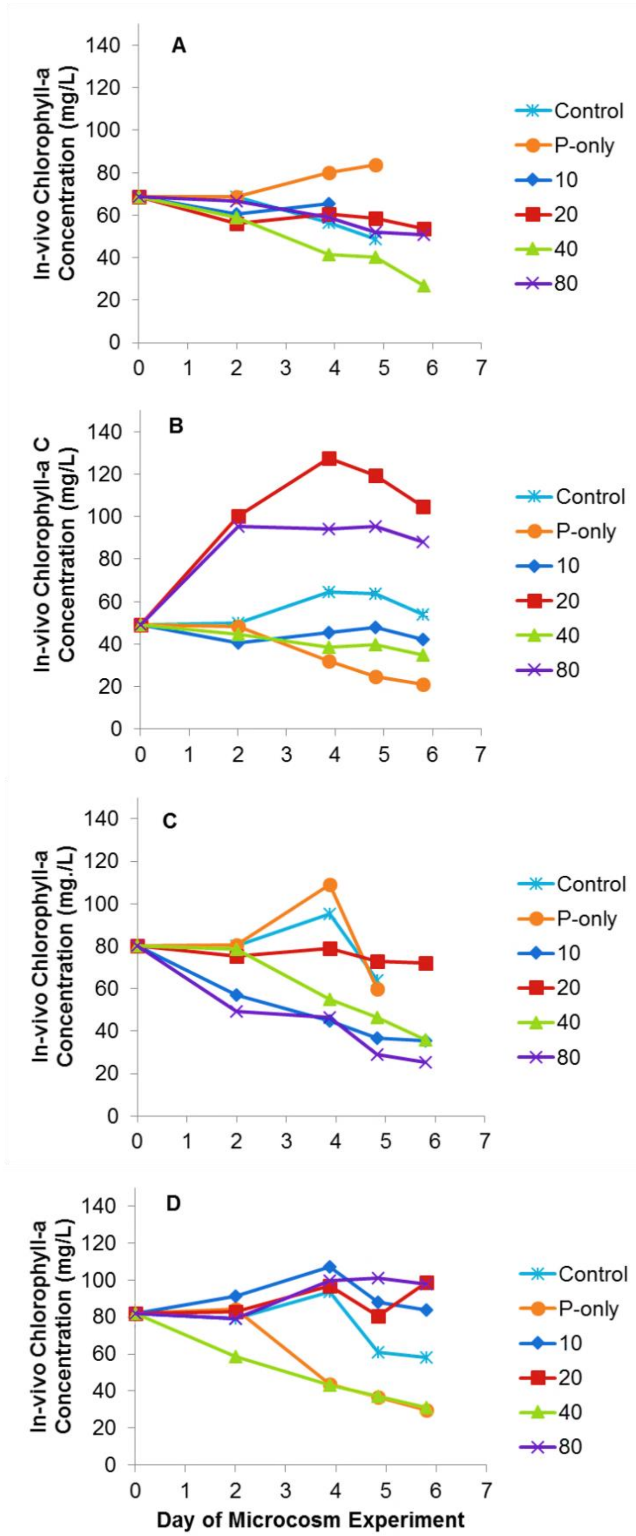

Figure 6. Microcosm in-vivo chlorophyll-a. (A) Ann, (B) Avalon, (C) Lomond, (D) Windsor.

When in-vivo chlorophyll-a showed a decline in biomass, the experiment was concluded.

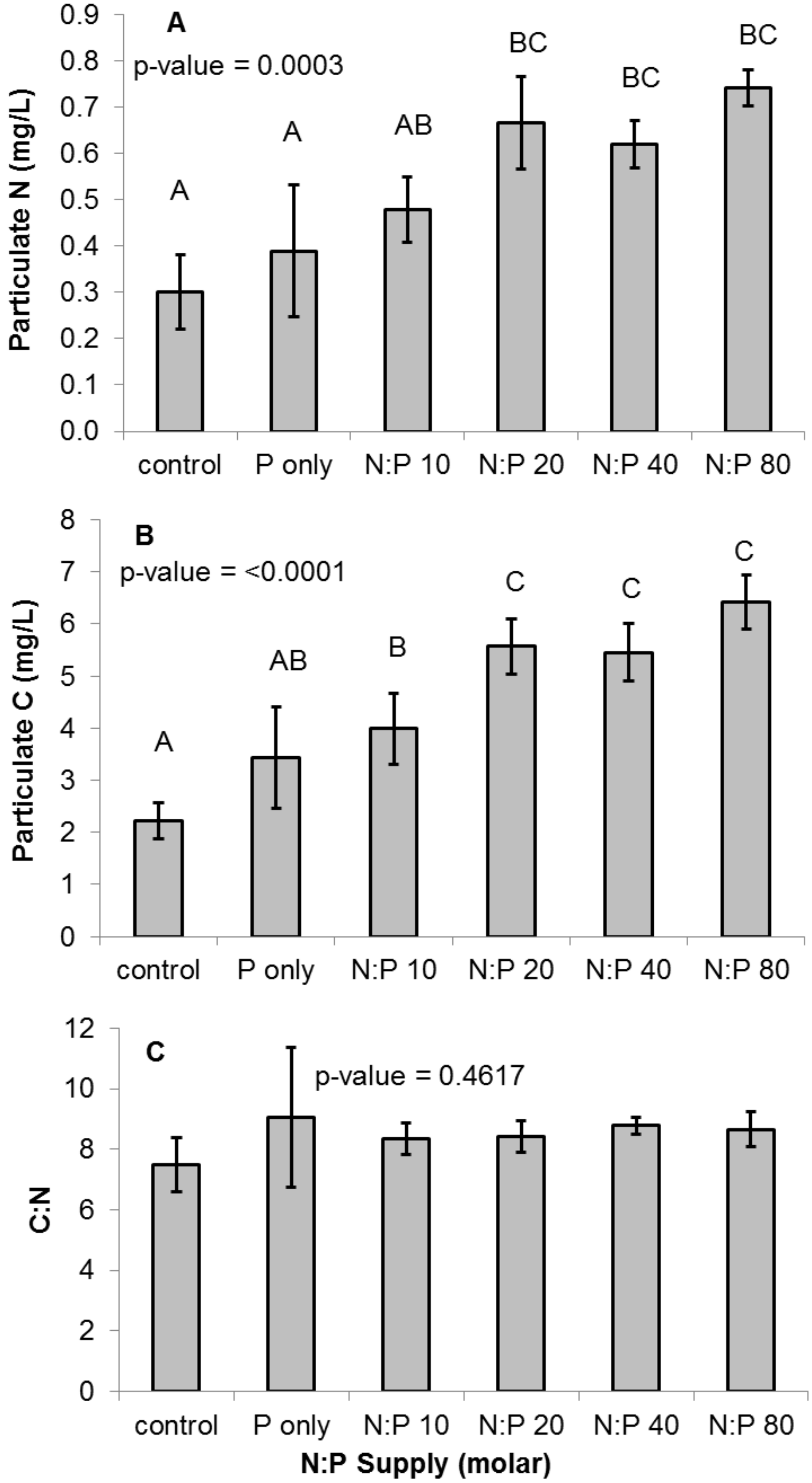

Figure 7. (A) Particulate N, (B) Particulate C and (C) C:N in Lake Ann microcosms.

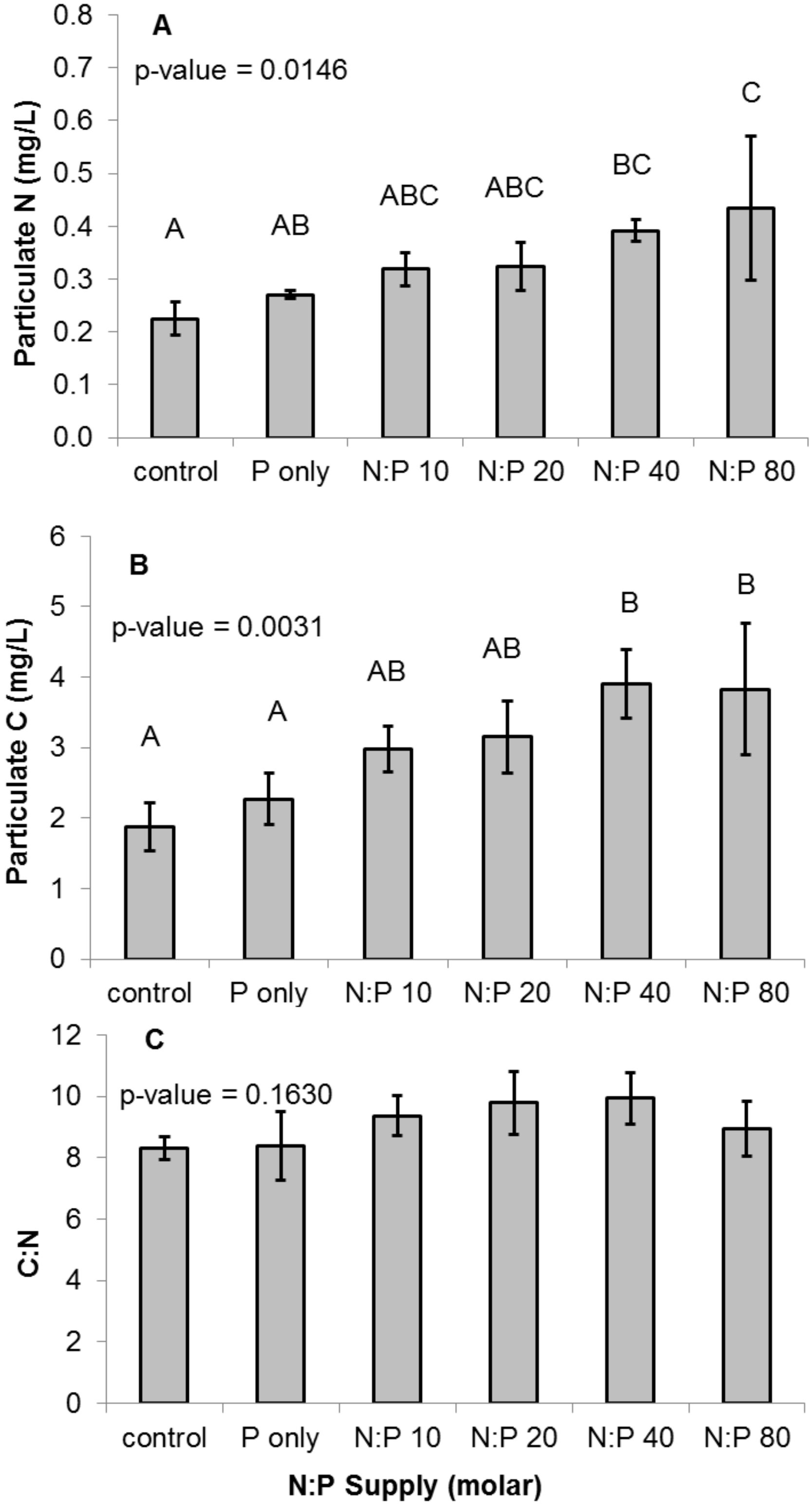

Figure 8. (A) Particulate N, (B) Particulate C, and (C) C:N in Lake Avalon microcosms.

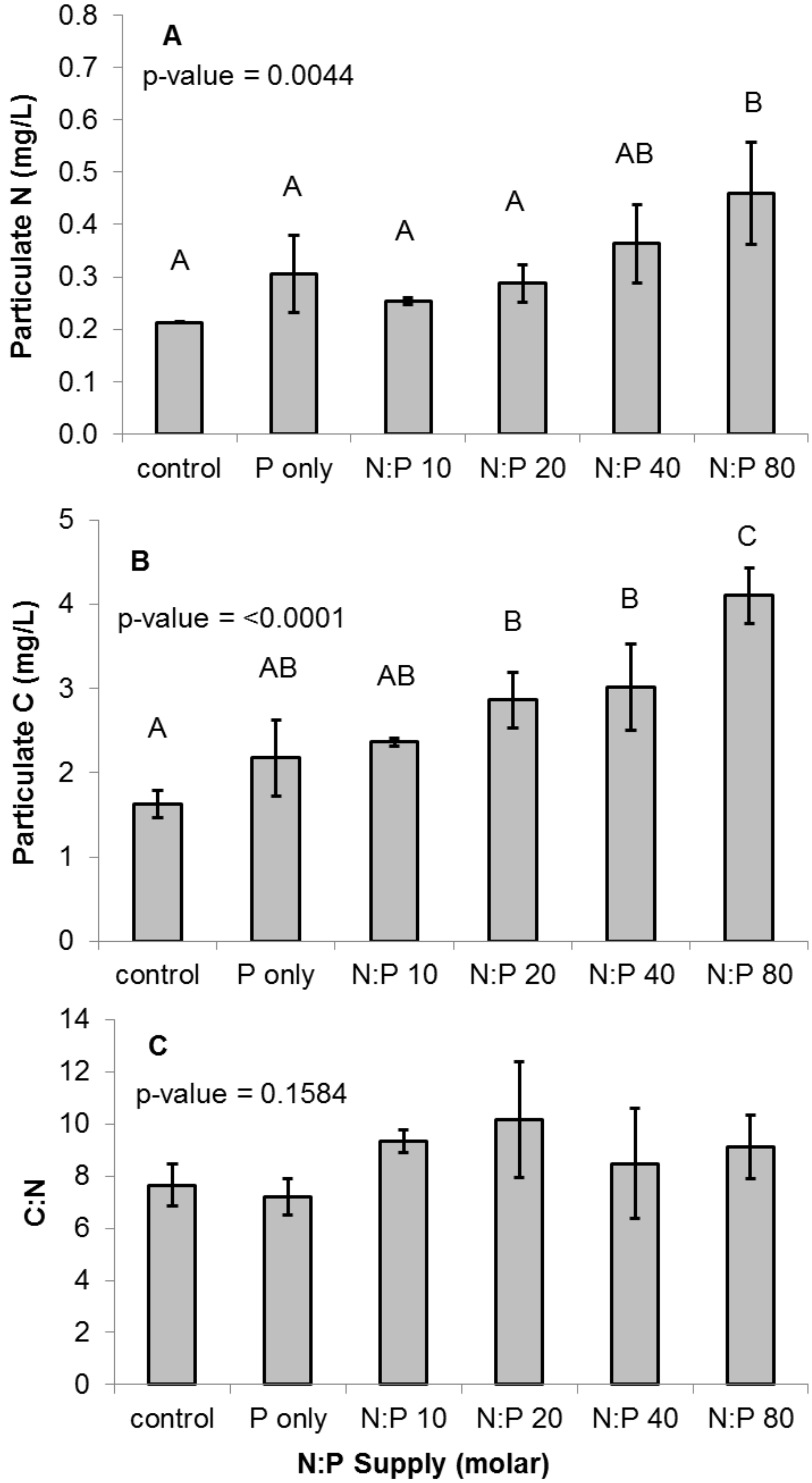

Figure 9. (A) Particulate N, (B) Particulate C, and (C) C:N in Lake Lomond microcosms.

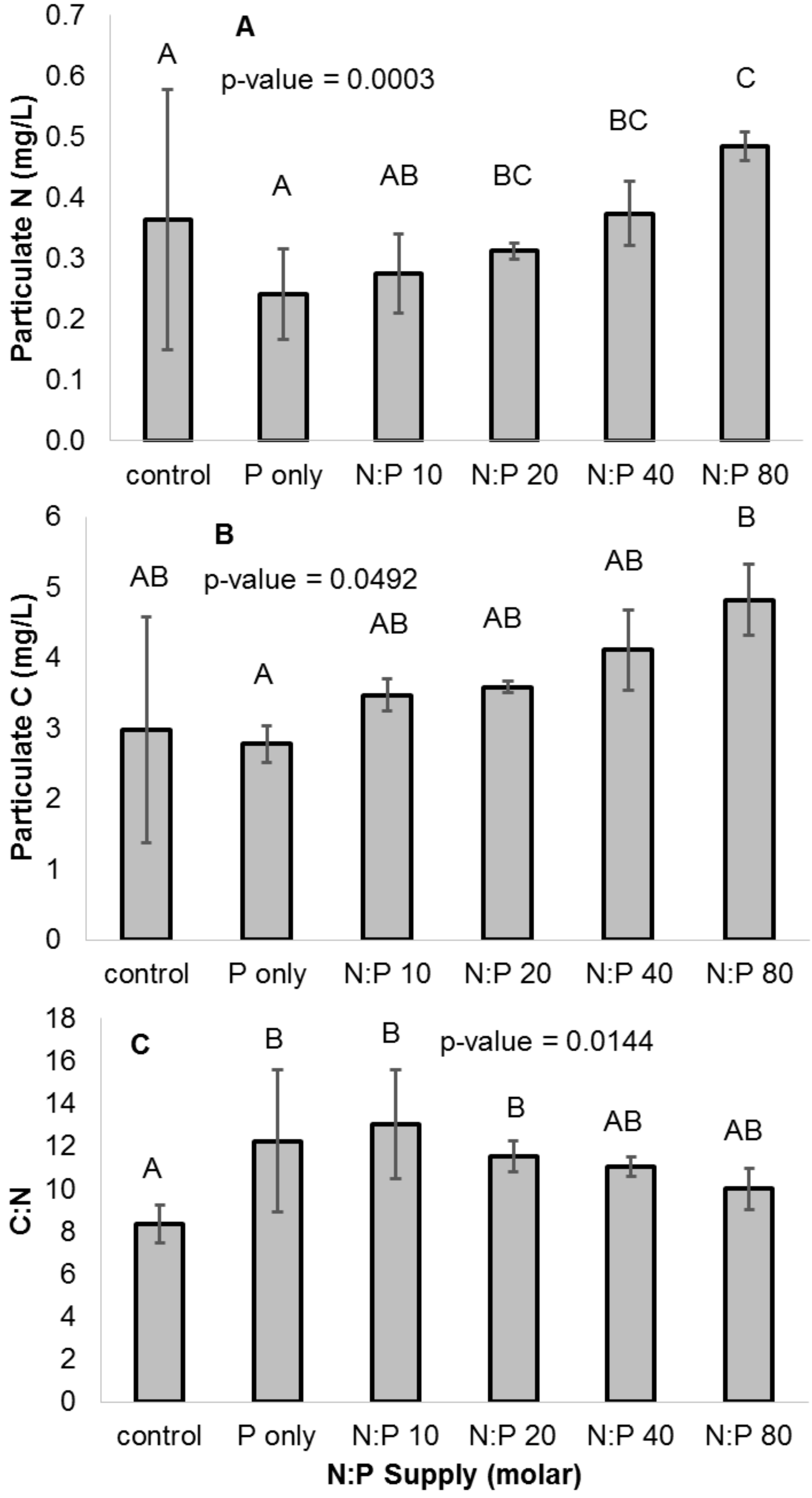

Figure 10. (A) Particulate N, (B) Particulate C, and (C) C:N in Lake Windsor microcosms.

Table 9. Low (N:P 10), high (N:P 80), and optimal (based on microcosm results) cost of fertilization in each lake.

Optimal Lake N:P	Pond Pro (10-34-0) application rate	Cost/Gallon	Lake Area (ac)	Urea (46-0-0) Application Rate	Cost/50 lb Bag	Fertilization Cost
Ann N:P 20	1-2 gallons/ac	$12.95	104.4	Dozens-hundreds of bags	$8	Low: $4.473.45 **Optimal: $6,993.03** High: $22,110.53
Avalon N:P 40			59.7			Low: $2,560.23 **Optimal: $6,889.10** High: $12,660.92
Lomond N:P 40			556.9			Low: $22,875.39 **Optimal: $64,233.68** High: $118,044.74
Windsor N:P 80			225.9			Low: $9,366.57 **Optimal: $24,782.81** High: $45,377.80